Multipath Routing Slice Experiments in Federated Testbeds

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Abstract. The Internet today consist of many heterogeneous infrastructures, owned and maintained by separate and potentially competing administrative authorities. On top of this a wide variety of applications has different requirements with regard to quality, reliability and security from the underlying networks. The number of stakeholders who participate in provisioning of network and services is growing. More demanding applications (like eGovernment, eHealth, critical and emergency infrastructures) are on the rise. Therefore we assume that these two basic characteristics, a) multiple authorities and b) applications with very diverse demands, are likely to stay or even increase in the Internet of the future. In such an environment *federation* and *virtualization* of resources are key features that should be supported in a future Internet. The ability to form slices across domains that meet application specific requirements enables many of the desired features in future networks.

In this paper, we present a Multipath Routing Slice experiment that we performed over multiple federated testbeds. We combined capabilities from different experimental facilities, since one single testbed did not offer all the required capabilities. This paper summarizes the conducted experiment, our experience with the usability of federated testbeds and our experience with the use of advanced measurement technologies within experimental facilities. We believe that this experiment provides a good example use case for the future Internet itself because we assume that the Internet will consist of multiple different infrastructures that have to be combined in application specific overlays or routing slices, very much like the experimental facilities we used in this experiment. We also assume that the growing demands will push towards a much better measurement instrumentation of the future Internet. The tools used in our experiment can provide a starting point for this.

J. Domingue et al. (Eds.): Future Internet Assembly, LNCS 6656, pp. 247–258, 2011.

1 Introduction

Multipath Routing Slices constitute a new transport service in future generation networks. *Network Virtualization (NV)* techniques [5,17] allow the establishment of such separate slices on top of a joint physical infrastructure (substrate). NV enables the parallel and independent operation of application-specific virtual networks (e.g. for banking, gaming, web) with their own virtual topology, naming, routing and resource management on top of a shared physical infrastructure. Virtual networks are denoted in NV as *slices* [15]. Slices that are not dedicated to a single application and that implement a general data transport service are designated as *routing slices* [13]. Routing slices as an architectural concept is known as *Transport Virtualization (TV)* [23,24]. These concepts have roots in the work on active networks, where the control plane of a router enabled applications fine-grained control of their own routing [6,11] and sharing of the resources at the routers using either constant or ad-hoc slices [16].

Slices, and routing slices in particular, are made up of shared resources that can be contributed by different administrative authorities. Thus, routing slices can be thought of as a *federation* [15] of networking resources, i.e., a combination of fractions of (virtual) links and (virtual) routers.

Due to the fine grained granularity of networking resources, routing slices have appealing features. Multiple paths between a single source and destination pair may exist in a slice and can be pooled in a *Multipath Routing Slice*. Such a multipath routing slice allows the use of alternative paths if a failure occurs and therefore improves resilience. A further application field of multipath transmissions is to obtain higher capacity between a source and destination pair. Packets can be distributed on the paths so that paths are used concurrently . As a result Multipath Routing Slices may pose the feature of *location transparency*, i.e., they permit data transport resource to be accessed without knowledge of their physical or network location.

Besides the establishment of routing slices and the instrumentation of federated environments with measurement functions, federation has also further challenges. The control and verification of service level agreements (SLAs) between domains as well as inter-domain security have to be addressed in federated testbeds as well as in the real Internet. Measurement functions can help to support this. Inter-domain SLA validation would profit from common data formats and data exchange among providers (e.g. [8]). Intrusion detection systems can increase situation awareness (and with this overall security) by sharing information. Nevertheless, the operators of the testbeds we considered in our setup are willing to cooperate. This is not always the case for (potentially competing) network operators in general. For this it is helpful to calculate cost and gain of sharing information with neighbors. Making these values explicitly known to the stakeholders can help to provide incentives for cooperation.

Although the concepts of Routing Slices and multipath routing slices are apparently favorable for future networks, the development of a network architecture (together with its protocols and mechanisms) based on these concepts is rather complex. Some questions that arise in the development process are for instance: *a)* how can (virtual) resources be configured to collaborate in slices, *b)* how can the performance of paths be measured to select them for pooling, or *c)* how does the performance of the system scale with the number of available networking resources?

Answering such questions comprehensively by means of mathematical analysis, simulations or experiments in local laboratories is often not possible. Applying analytical methods often requires assumptions that reduce the applicability of solutions. Simulation requires not only the modeling of the problem space but also requires knowledge about and integration of potential parameters that can influence results. If results depend on many parameter, the applied level of abstraction might be too coarse. Working with models requires many simplification that can lead to unrealistic results. Tests in labs suffer from scalability limits since physical distances and the number of resources are limited. Also the acquisition of specific measurement equipment is often difficult in local labs due to the high costs of such hardware. In short, as network scientists, we need larger testbeds in order to supplement theoretical analysis and validate theoretical results by experiments in large-scale highly distributed environments and under real network conditions.

The experimental facilities as provide by the the European FIRE program [1], the US-American GENI [10] and VINI systems [4], or the German G-Lab [20], aim at fulfilling these requirements. A federation of them provides the required scalability features (e.g. large distances between entities) and allows the use of special equipment and features that are only available in specific testbeds. The federation of testbeds can give new insights for federating resources in general and therefore for the design of networking architectures that are made up of federated resources, like multipath routing slices. However, todays testbeds are typically customized to particular user groups and offer different capabilities and interfaces. The federation of them still requires research on how these facilities should interconnect with each other in order to unleash the true benefits of federation resulting from the broader set of available features and functions.

In this paper, we present a multipath routing slice experiment that we performed over multiple federated testbeds. Since there was not a single testbed that could offer all the capabilities we needed, we combined capabilities from different experimental facilities (G-Lab, PlanetLab Europe, and VINI). While a measurement instrumentation of testbeds is essential to path selection in multipath routing slices, we additionally require highly precise measurements in our experiment. Therefore, our contribution is threefold. We present in the paper *a)* our experiment (setup, results, findings), *b)* our experience with the usability of federated testbeds and *c)* the use of advanced measurement technologies in experimental facilities.

The paper is structured as follows: in Section 2, we introduce the objectives and requirements of the multipath routing slice experiments. Section 3 describes the federation and setup of testbed systems for the experiment. Section 4 outlines the results of the experiments which validate an analytical performance model for multipath transmissions. Section 5 describes the lessons learned during the

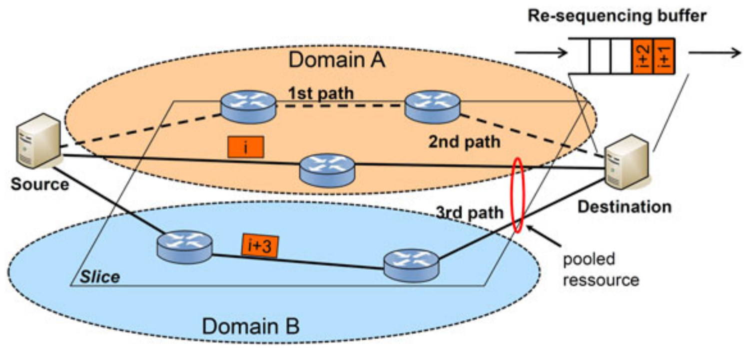

Fig. 1. Multipath transmission slice

experimental setup in the federated experimental facilities. Section 6 discusses the sharing and joined use of measurement equipment and tools. Finally, Section 7 provides a brief summary and outlook to the enhancements of federated facilities.

2 Experiment Objectives and Requirements for a Concurrent Multipath Transport

Alternative multipath transport services in future federated networks might employ concurrent or consecutive packet transmission. Concurrent transmission techniques have recently been receiving a lot of attention due to their advantages in resource pooling [22]. The strong interest has also been witnessed by recent research projects such as Trilogy [21] or state-of-the-art protocols like SCTP-CMT [7] and Multipath-TCP [14]. For the case of Concurrent Multipath Transmissions (CMT), different transport resources are pooled together and appear to be one single virtualized transport resource. However, different path characteristics such as one way delay, capacity or jitter of the pooled resources lead to a different behavior than in the case of a single resource. Different path delays inevitably lead to out-of-order arrivals at the destination. An effect that does not, or at least does not appear within this dimension, on a physical link. The right order within the packet stream can be restored by a re-sequencing buffer, as proposed and analyzed theoretically in [24]. The investigated architecture and the measurement setup is illustrated in Figure 1. The federation of resources is outlined by the use of concurrent transmission paths from different domains.

We build a model for such a re-sequencing buffer and try to predict the buffer occupancy based on network conditions. The main purpose of our experiment is the validation of the proposed model. For that, one way delay distributions of the different paths, i.e., the input parameter of the model, and the re-sequencing buffer occupation, i.e., the output parameter of the model, have to be measured. In order to conduct the desired measurements the experiment has the following requirements concerning testbeds: a) The possibility to set up a routing overlay to emulate the multipath transport. b) A large distributed set of nodes in order to get a high diversity of different path delay values. This enables a verification of the model with an adequate amount of different configurations. c) Advanced measurement methods for high precision and hop-by-hop one-way delay measurements.

3 Experiment Setup

We investigate the capabilities of different testbeds in order to find a suitable testbed that fulfills the needs of our experiment. Table 1 describes the differences of PlanetLab Central (PLC), PlanetLab Europe (PLE), German Lab (G-Lab), and the VINI testbed. It can be seen that a single testbed is not able to cope with the tight requirements for our multipath experiment. G-Lab allows exclusive reservation and installation of arbitrary software but is only distributed within Germany, has a limited access, and currently provides no federation method. PLE, PLC, and VINI can be federated by the Slice Federation Architecture (SFA), but only VINI provides a routing configuration service. We therefore used manually configured overlay routing on application layer to combine PLE and G-Lab with VINI. PLE is the only network that additionally provides the advanced measurement tools that we need for our experiment. In order to verify results we used both, passive and active measurement tools. Active measurements provide a statement about the network situation and require the injection of test traffic. Passive measurements measure the experiment's traffic itself and therefore provide a statement about the real treatment of the traffic in the network. We used the network of distributed ETOMIC nodes, which is federated with PLE under the OneLab federated experimental facilities [3] and multi-hop packet tracking [18], which is available in PLE. Figure 2 shows a screenshot of the visualization for the passive measurements with the packet tracking tool. The tool is available at [2].

Our setup, depicted in Figure 1 consists of a source, a destination and different paths between source and destination. The packet forwarding was realized either by application layer packet forwarding over different hosts or different paths configured in VINI. For our packet layer forwarding setup we used ETOMIC nodes which provide high precision GPS synchronized timestamps and

Table 1. Comparison of different experimental facilities

Feature	G-Lab	PLE	PLC	VINI
Scope	Germany	Europe	World	Mainly US
Exclusive Reservation	Yes	No	No	No
Routing	with own tools	with own tools	with own tools	Yes
Bandwidth and QoS	with own tools	Planned	Planned	Yes (service)
Openness/Federation	No (tests planned)	Yes (SFA)	Yes (SFA)	Yes (SFA)
Tools/Packet Tracking	individually	Yes (service)	individually	individually
Clock Sync	NTP	NTP, some GPS	NTP	NTP

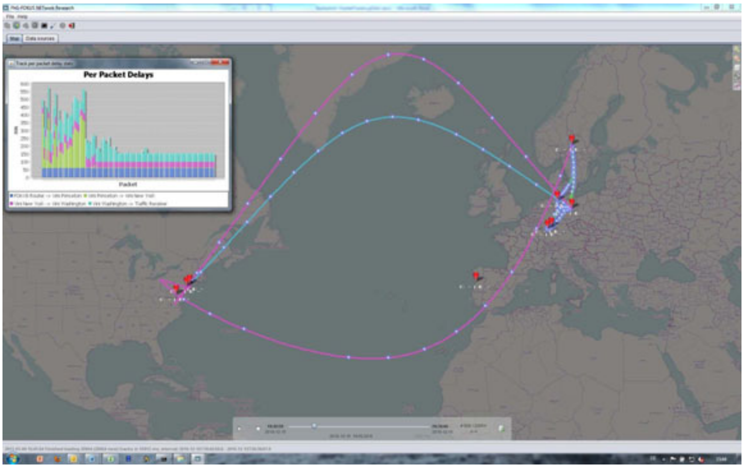

Fig. 2. Visualization for the passive measurements with the packet tracking tool

thus enabled us to measure one way delays of each packet. However, the experimental setup was very complicated since the different paths had to be set up manually. For the experiments with VINI the setup of a multipath transmission experiment was much easier. Since our end nodes did not provide the required measurement precision we utilized multi-hop packet tracking [18] for conducting one way delay measurements.

For the performed experiment we emulated a concurrent multipath transmission via two different paths. We transmitted 100.000 packets over each of the used paths. The packets were scheduled in a round robin manner with an inter-packet-time of 10 ms on each path. We measured the buffer occupancy at the receiver and the measured one way delay, once measured actively and once measured passively, as described above. The results of our experiments are discussed in the next section.

4 Experimental Results for Multipath Routing Slices

This section summarizes results of the experiments we conducted for a concurrent multipath transmission as outlined in [24]. We sent every ten milliseconds two packets from the source to the destination via two different paths. First, we discuss active measurements performed in PLE with support of the ETOMIC measurement system. After that we outline the passive measurements [18] conducted within GLAB and VINI.

4.1 Active Measurements with PLE and ETOMIC

For the measurements we used ETOMIC nodes with DAG cards located in Pamplona and Elte as source and destination. The packets were transmitted via two different paths, one via a PLE node located in Vrije, one via a node in Tromso.

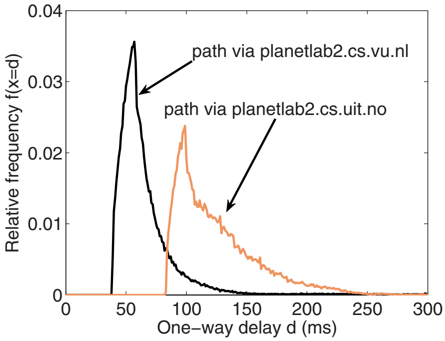

Fig. 3. Actively measured one-way delays as relative frequencies for two different paths within PLE

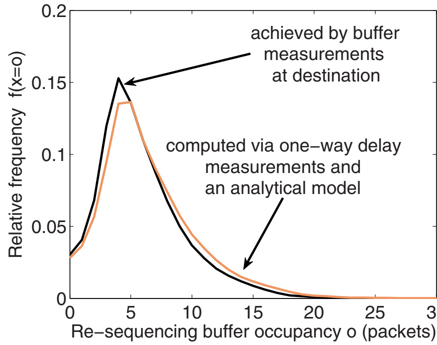

Fig. 4. Comparison between actively measured and estimated re-sequencing buffer occupancy

The one-way delay in milliseconds is depicted as relative frequencies in Figure 3. It can be seen that the path delay via Vrije is smaller than the path delay via Tromso. Further, the one way delay values range in an interval of more than 100 milliseconds, i.e. the delay values for the packets are highly variable during the measurements. Based on these measurements, the occupancy of the re-sequencing buffer can be approximated by the analytical model.

Figure 4 illustrates the observed re-sequencing buffer occupancies in packets. It can be seen, that the probability for an empty buffer is very low, and that most likely five packets are stored within the buffer. This is due to the fact that packets sent via Tromso experience higher one way delays than packets sent via Vrije. In addition, higher buffer occupancies may also occur.

Further, the estimated re-sequencing buffer occupancy is also depicted in Figure 4. It can be seen that the gap between the buffer occupancy computed with the analytical model and the measured buffer occupancy is very small. Thus, we can conclude, that for the given scenario the prediction of the model is very accurate.

4.2 Passive Measurements with VINI and GLAB

For these experiments we configured one path via a GLAB node in Darmstadt and a second one via VINI. The one-way delays of the packets were captured by passive multipoint measurements, cf. [18].

The measured one-way delay is depicted as relative frequencies in Figure 5. The figure shows that the path delay via GLAB is smaller than the path delay via VINI and rather constant. Further, the one way delay values on the VINI path range in an intervals of more than 100 milliseconds, i.e. the delay values for the packets are highly variable during the measurements. That is due to the fact that we injected additional random delay on this path.

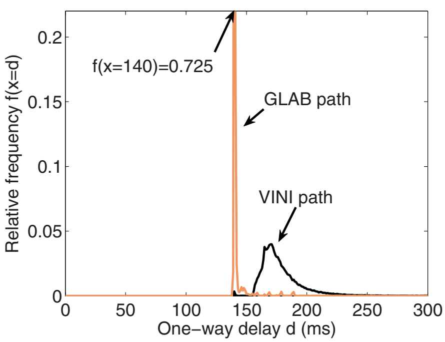

Fig. 5. Passively measured one-way delays for two different paths within GLAB/VINI

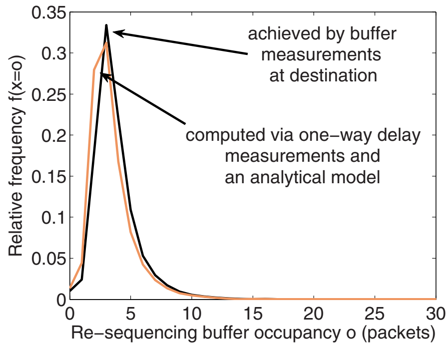

Fig. 6. Comparison between measured and estimated re-sequencing buffer occupancy

The measured buffer occupancy as well as the the analytical approximation is depicted in Figure 6. It can be seen tat most likely up to 10 packets have to be stored in the buffer. In addition, due to the varying one way delays higher buffer occupancies may also occur. Again the gap between measured and computed buffer occupancy is very small, i.e. the model is again very accurate.

The discussed measurements were conducted separately, i.e., under different conditions. However, the significance of the results could be improved by conducting passive and active measurements concurrently.

5 Lessons Learned for the Usage of Federated Experimental Facilities

In this section we summarize our experience in the federation of experimental facilities in the course of our experiments. First, we detail the lessons we learned while using different testbeds, then we describe the observations we made for each of the used testbeds.

5.1 Challenges while Preparing the Experiments

First we present the challenges which occurred during the experiments.

Booking of Resources With the SFA software it was possible to book nodes in PlanetLab, PlanetLab Europe and in the VINI Testbed. The Glab testbed is designed as an exclusive testbed for experimenters that participate in the G-Lab project. Thus, G-Lab does not provide a federation interface yet. Therefore, G-Lab nodes were booked separately and connected manually to the overlay. Although G-Lab was designed as an exclusive resource, some tests for the integration with SFA and the PII Framework are planned. By federating the different facilities the efforts needed for resource booking upon the different testbeds could be reduced.

Configurable Routing Slice A configurable routing topology was essential for our experiments. As we had to employ a routing infrastructure over multiple testbeds to match our requirements it would have been beneficial to use a federation framework like SFA or the PII framework to configure the topology, but both frameworks do net yet support overlay creation. In order to resolve this issue, we established tunnels between the nodes of the different testbeds. Especially PlanetLab and PlanetLab Europe lack a standardized way to configure the topology and the routing protocol. Further, only one virtual interface is configurable and the configuration is restricted, e.g. one cannot change flow or routing table entries. Thus, we utilized application layer overlay routing techniques for transmitting packets via different paths, i.e., we set up a routing topology manually. VINI on the other hand provides an easy-to-use topology creation, configuration of interfaces and the use of arbitrary routing protocols. Further, it also allows the emulation of link characteristics and the booking of guaranteed bandwidth. However, VINI provides only a few number of nodes, which are mainly located in the US.

Observation tools Our experiments are strongly dependent on precise observation tools that capture the experiment result and environmental conditions. By using different testbeds, we had the possibility to use adequate tools which allowed separated active and passive measurements. However, due to the different methods, the comparability of the results is reduced. Here, common observation methods or a common understanding how the provided tools differ would enhance the comparability and, thus, the value of the gained results. An initiative pushing activities in this field is the OneLab project which launched Free T-Rex [2], a website dedicated to information about *Free Tools for Future Internet Research and Experimentation.* The Advanced Network Monitoring Equipment (ANME) deployed by the Onelab project within Planetlab Europe includes precise network cards for active delay measurements using ETOMIC and the continuous monitoring platform (CoMo) for passive measurements. This enables high precision active and passive measurements in parallel and thus allows a comparison between active and passive measurement methodologies.

Clock Synchronization For our experiment we required precise active and passive one way delay measurements. Nevertheless, the achievable accuracy of such measurements depends on the synchronization status of the involved observation points. The ETOMIC boxes used in our experiment are GPS time synchronized and meet our precision requirements. A general clock synchronization service across testbeds, in the best case supported by GPS-based clocks, would help to provide more accurate measurements.

5.2 Observations on the Single Testbeds

Regarding the use of the particular testbeds we provide the following observations.

G-Lab provides an exclusive resource. We can book nodes exclusively and can generate a much better controllable environment. We can install and use arbitrary software on the G-Lab nodes. We assume that such features are of interest for many experimenters, but the closed nature of G-Lab makes it unavailable for experimenters that do not participate in a G-Lab project. A further disadvantage of G-Lab is that it has a comparatively small number of nodes and the nodes are only in Germany, therefore it is not suitable for experiments that require real Internet conditions with regard to scale, delay values, and geographical distribution of nodes.

PlanetLab Europe offers many additional functions, research tools and hardware to support active and passive high precision measurement. Such an infrastructure helps experimenters to perform measurements and retrieve accurate results. But neither PlanetLab nor PlanetLab Europe provide routing support. Due to this we had to invest a lot of effort to manually set up tunnels for a routing topology.

VINI is very well suited to provide routing support. VINI also supports SFA, so nodes could be booked via SFA with the same credentials we used for PlanetLab Europe. The disadvantages of VINI is that it only provides a few nodes, which are mainly in the US. Furthermore, not all nodes have public Internet access, which makes the configuration more complicated. Another issue that came up during our experiments is that the VINI infrastructure is too good, i.e., the delay on a path is very low. Since we had no GPS clock synchronization we could not capture the delay between two hops in the precision required for the transmission speed.

6 Sharing and Standardizing Measurement and Observation Tools

As part of our work we have seen the need for all the heterogeneous experimental facilities to standardize experiment measurements and observation tools, not only to capture the outcome of the experiment but also to log the experimental conditions. Free T-REX [2] provides a platform for testbed users, testbed operators and developers to offer their measurement results and software tools to the public and to share their experience. Further, free T-Rex seeks to employ standardized instruments to improve the comparability and openness of scientific results in the field of future Internet research. The platform gives an overview of available tools in future Internet experimental facilities and, based on user feedback, the tools' feasibility for experiment requirements can be assessed. Another objective is to create links to relevant groups and support standardization efforts in the field of research experiment observation.

Free T-Rex offers such valuable resources like access to the MoMe [12] trace and tool database and measurement services, the employed packet tracking service [18], TopHat [9], and the DIMES [19] infrastructure.

7 Conclusion

In this paper, we outlined how the federation of multiple experimental facilities can contribute to an improved design of future, federated Internet architectures. We described how federated transmission resources can be exploited for multipath routing slices and how this may form a new concept for network architectures. For that, we validated an analytical model of a multipath routing slice mechanism by measurements in federated testbeds. We showed why isolated testbeds are insufficient for some of the experiments and identified difficulties and requirements for federated testbeds. Our experiment would not have been possible in available non-federated testbeds. In this way, the federation of testbeds enabled a truly comprehensive evaluation of the proposed multipath routing slice mechanisms. The experiments and their results have demonstrated that the federation of experimental facilities is very powerful to accelerate the design of future networks. Although the advantages are striking, the usage of the testbeds and the federation of the facilities is still painful. Booking of resources was easy, but the configuration of a federation on the routing layer or below this layer and of the shared measurement equipment requires still huge efforts. If such federations were made easier, the full power of federated testbeds and of federation for future networks might be truly unleashed.

Acknowledgements The research leading to these results has received funding from the European Union's Seventh Framework Program (FP7/2007-2013) under grant agreement n° 216366 for the NoE project "Euro-NF". In particular, it was funded through the Euro-NF specific joint development and experimentation project "Multi-Next". Furthermore, we would like to express our appreciation for the support through the experimental facilities GLAB, PLE and ETOMIC and the projects VINI and ONELAB. Further, the authors deeply want to thank Andy Bavier for his support during the course of this work.

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